STATE OF CONNECTICUT
DEPARTMENT OF ENVIRONMENTAL PROTECTION
79 Elm Street
Hartford, CT 06106-5127
http://dep.state.ct.us
Arthur J. Roque, Jr., Commissioner

LONG ISLAND SOUND AMBIENT WATER QUALITY MONITORING PROGRAM:

Summer Hypoxia Monitoring Survey 1991-1998 Data Review

NICHOLAS P. KAPUTA
CHRISTINE B. OLSEN

Bureau of Water Management
Planning and Standards Division
79 Elm Street
Hartford, CT 06106-5127

Funding provided by the U.S.
Environmental Protection Agency
Long Island Sound Study

LONG ISLAND SOUND STUDY
A Partnership to Restore and Protect The Sound

September 2000

Cover photos: Matthew Lyman

Inquiries related to the contents of this document, or any question regarding the DEP's ongoing water quality monitoring efforts in Long Island Sound should be directed to:

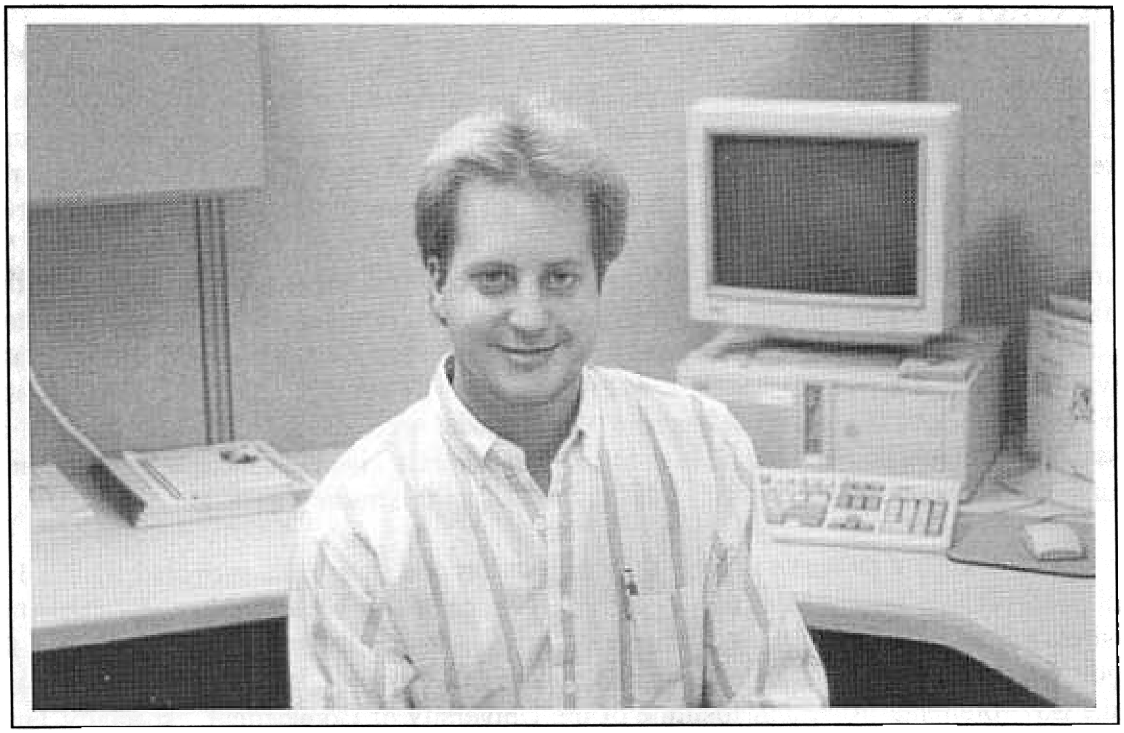
Long Island Sound Ambient Water Quality Monitoring Program staff (see below)
at
CTDEP Bureau of Water Management
Planning and Standards Division
79 Elm Street
Hartford, CT 06106-5127

Christine B. Olsen
Phone: (860)424-3727
E-mail: christine.olsen@po.state.ct.us
program oversight, reporting, data analysis, QA/QC

Matthew Gates
Phone: (860)424-3292
E-mail: matthew.gates@po.state.ct.us
database management, hypoxia area mapping, data requests, field operations, scheduling and cooperative requests

Matthew Lyman
Phone: (860)424-3158
E-mail: matthew.lyman@po.state.ct.us
CTD data management, cruise summaries, webpage development, field operations, regional monitoring work group contact

Visit the Long Island Sound Water Quality Monitoring Program web page, with Program information and data. Under construction at:
http://dep.state.ct.us/wtr/lis/monitoring/lis_page.htm



IN MEMORY

Nicholas P. Kaputa, Environmental Analyst 2 with the CTDEP Bureau of Water Management's Long Island Sound Water Quality Monitoring Program since January 1995, lost a year and half battle with cancer on June 20, 1999. Nick's history with the Department goes back to 1989 when he began his association with the Inland Fisheries Division, working as a seasonal employee, and, as a graduate student at the University of Connecticut, performing his Master's thesis work on the fishes of the lower Housatonic River. We mourn the loss of a hard-working colleague who took on an extensive field sampling program with apparent ease. Through a conscientious effort to make it the best it could be and a high level of personal initiative he has left us with high quality data, an efficient and organized data handling and database system, and the information and training we need to keep it all going. We miss his capable mind and hands in charge of the monitoring effort - fixing equipment and cables, organizing, analyzing and interpreting a cumbersome data set. We miss his ready smile, his sense of humor, and his honesty. We miss our very capable friend.

The following is Nick's effort, his report, that he never had the pleasure of seeing in this final form.

Christine Olsen and Paul Stacey
CTDEP Bureau of Water Management
Hartford, Connecticut
January 2000

ACKNOWLEDGMENTS

We would like to acknowledge the work of numerous past and present employees of the CTDEP Bureau of Water Management's Long Island Sound Water Quality Monitoring Program whose time both in the field and the office contributed significantly to this data collection and reporting effort: Christopher Bellucci, Daniel Biron, Nathan Denslow, Mark Fallon, Carla Farris, Jason Flaherty, Mark Foreman, Matthew Gates, Douglas Jann, Michael Kovacs, John Lake, Matthew Lyman, Julie Millus, Amy O'Neal, and George Smith. Additionally we would like to thank the staff of the Bureau of Natural Resources Fisheries Division for their previous and continued support in our sampling efforts, especially: Mark Alexander, Kurt Gottschall, Mark Johnson, and David Simpson. We also give great thanks to the crew of the R/V *John Dempsey*, Miles Peterle and Peter Simpson, for their considerable efforts in the logistics of the operation of the research vessel and the substantial task of assisting our program's biweekly monitoring of Long Island Sound during the summer months for the eight years of this survey.

We would also like to acknowledge the cooperation and assistance provided by the Interstate Sanitation Commission, especially Peter Sattler, and the New York City Department of Environmental Protection Marine Sciences Section, especially Bernadette Boneicki, for their ongoing water quality sampling efforts and their contribution of data to this effort. Thanks also to the Environmental Research Institute of the University of Connecticut, especially Jan Heitert and the nutrient laboratory staff, for their cooperation and commitment to fulfilling all of our analytical needs.

This work was partially funded by the U.S. Environmental Protection Agency, through the Long Island Sound Study, under sections 320 and 119 of the federal Clean Water Act.

Long Island Sound Summer Hypoxia Monitoring Survey
1991 - 1998 Data Review

EXECUTIVE SUMMARY

The Connecticut Department of Environmental Protection, Bureau of Water Management, initiated the Long Island Sound Ambient Water Quality Monitoring Program in January of 1991 to establish a chemical and biological database necessary to monitor trends in water quality throughout the Sound. The purposes of this report are to: 1) describe the summer dissolved oxygen monitoring survey; 2) provide a review of the 1991 through 1998 summer dissolved oxygen and hydrographic data collected; 3) depict trends in observed summer dissolved oxygen concentrations and other observed parameters over the first eight years of monitoring (1991 through 1998); 4) establish and provide baseline statistics that can be used to evaluate the course of future trends in dissolved oxygen; and 5) provide data for research and modeling activities in the region.

Annual summer dissolved oxygen monitoring surveys consisted of sampling approximately every other week from mid-June through September each year. In the first three years of this study (1991-1993), sampling was conducted as part of a cooperative intra-agency effort with CTDEP Fisheries Division to evaluate dissolved oxygen (DO) conditions and coincident fish abundance. This effort was supplemented by monthly water quality monitoring at seven axial master stations from Throgs Neck in the west to Fishers Island in the east. Beginning in 1994, forty-eight permanent stations were established and six to seven sampling cruises were conducted each summer season. Stations were sampled for dissolved oxygen, temperature, salinity, photosynthetically-active radiation (beginning in May 1992), and chlorophyll *a*.

The duration, area and severity of low dissolved oxygen conditions varied annually in Long Island Sound. Although hypoxia (defined as DO less than 3.0 mg/L) was typically present in the Sound by early July, the observed onset ranged from July 1 in 1994 to August 10 in 1996. Additionally, the duration of hypoxic conditions ranged from a low of 34 days in 1996 to a high of 78 days in 1993. The maximum area of hypoxia occurred in 1994 with an area of 1022 km^2 impacted. In 1997, only 77 km^2 of the Sound's bottom waters were hypoxic. Short and long-term weather patterns, particularly those that affected water temperatures, stratification and mixing in the Sound had an important influence on the extent of hypoxia.

The survey results revealed an increasing (improving) trend in summertime bottom water DO concentrations throughout most of the Sound. Five stations, one in the Narrows, one in the Western Basin, two in the Central Basin, and one in the Eastern Basin, experienced significantly increasing DO levels ($p<0.05$). Thirty-three additional stations also showed trends of increasing DO, although these were not statistically significant ($p>0.05$).

This work was partially funded by the United States Environmental Protection Agency's Long Island Sound Study. Questions regarding this report and requests for additional data or information from the Long Island Sound Ambient Water Quality Monitoring Program should be brought to the attention of the Planning and Standards Division of the Bureau of Water Management.

CONTENTS

CONTENTS (continued)

APPENDICES

List of Figures

List of Figures (continued)

List of Tables

Long Island Sound Summer Hypoxia Monitoring Survey
1991 - 1998 Data Review

INTRODUCTION

Background

Initiated in 1985, the Long Island Sound Study (LISS) is a partnership of federal, state, and local governments agencies, private organizations, and citizens formed to develop and implement a comprehensive conservation and Management Plan (CCMP) for Long Island Sound. Funding support for the LISS is provided by the EPA through the National Estuary Program and by the states of Connecticut and New York. One of the primary missions of the LISS is to collect data and assess the environmental conditions of the Sound. During 1988, 1989 and 1990, a series of comprehensive field surveys was conducted to complement the development of a coupled hydrodynamic-water quality model being prepared as part of the federal National Estuary Program's Long Island Sound Study (LISS) by the National Oceanic and Atmospheric Administration (NOAA) and HydroQual, Inc. These surveys provided physical, chemical, and biological water column data essential to calibrate and verify the Long Island Sound model. Surveys were conducted by the Marine Sciences Institute (MSI) of the University of Connecticut, the Marine Sciences Research Center (MSRC) of the State University of New York at Stony Brook, and the New York City Department of Environmental Protection (NYCDEP), and were supported by the Environmental Protection Agency□s (EPA) National Estuary Program. The 1988-1990 work significantly expanded the database developed during the preceding two years of the LISS, detailing water temperature-salinity structure throughout the Sound and providing the first comprehensive set of synoptic current and water quality data. The data were essential to modeling efforts and to the management strategy development and implementation activities that followed.

In January of 1991 the Connecticut Department of Environmental Protection (CTDEP) initiated a water quality and hydrographic survey to provide continuity to the LISS data set and to ensure that data would be available as the LISS progressed into the implementation phase. This survey continues in an expanded form with EPA support as the Department's Long Island Sound Ambient Water Quality Monitoring Program (the "Program").

Over the long-term, the data from this Program are essential to assess trends in water quality, especially responses to implementation of the LISS *Comprehensive Conservation and Management Plan* (CCMP) recommendations (LISS 1994). Nitrogen enrichment in particular has been determined to be a primary cause of low dissolved oxygen conditions in the Sound. Reducing the loading of this nutrient is a major goal in the management actions being taken by the LISS and participating jurisdictions to improve the health of the Sound. In particular, the data will allow the Department and the LISS to assess the effectiveness of management actions taken to reduce nutrient inputs to the Sound. The purpose of this survey is to document summer dissolved oxygen conditions throughout Long Island Sound.

Goals and Objectives

The goals of the Department's Long Island Sound Ambient Water Quality Monitoring Program are:

- to monitor water quality parameters year round on a monthly schedule at stations throughout Long Island Sound
- To monitor the temporal and spatial extent of summertime hypoxia through Sound-wide sampling every other week from late June through mid-September
- To maintain a long-term database of the information collected

The objectives of the Program are:

- To review the data periodically, in combination with available historical data, for trends
- To assess the long-term results of specific management actions such as the "no-net increase" nutrient (nitrogen) policy adopted in 1990 and the nutrient reduction strategy implemented in 1994
- To provide state and federal managers and policy-makers with information on existing conditions and trends that can be used in the development, implementation and assessment of strategies to control and improve water quality in the Sound
- To make the data available for related efforts such as research and water quality model development and calibration
- To make data available to other interested individuals/groups

Hypoxia

The Long Island Sound Study has defined hypoxia as low concentrations of dissolved oxygen, less than 3.0 milligrams per liter (mg/L), in water. Specifically, "hypoxia" refers to the low dissolved oxygen condition that develops each summer in the bottom waters of Long Island Sound (LISS 1994). Hypoxia has been identified as the most pressing problem affecting the health of the Sound in the *Comprehensive Conservation and Management Plan* (LISS 1994). In general, the key factor that promotes the development of hypoxia in the Sound is the presence of excess nutrients, especially nitrogen. Nitrogen is a natural and necessary nutrient for a healthy estuarine ecosystem, but is found in Long Island Sound in concentrations much higher than would naturally occur. These high concentrations are due to inputs from anthropogenic sources such as sewage treatment plants, industry, land runoff, and atmospheric pollution. Excess nitrogen contributes to the excessive growth of phytoplankton, the microscopic plants that are abundant in the Sound's waters. When the phytoplankton die, they sink to the bottom where natural decomposition of this organic matter takes place, consuming oxygen in the process. During the summer months, stratification of the water column restricts the mixing of oxygen-rich surface waters with bottom waters. Consequently, dissolved oxygen becomes depleted in the bottom waters as reoxygenation through the action of winds, waves, currents, and photosynthesis is absent or insufficient. Hypoxia stresses fish and other marine organisms, reducing feeding and growth and decreasing the amount of suitable habitat available to them. In severe cases, hypoxia can result in mortality of exposed organisms.

Excess nitrogen and the abundant phytoplankton blooms it supports are key factors in the development of low dissolved oxygen (or hypoxic) conditions in LIS. However, the characteristics of each year's occurrence, including annual variability in the timing, duration, spatial extent, and severity of the hypoxic event, are largely driven by weather conditions. The timing and strength of summer stratification, which is important to the development of hypoxia, depend on winter, spring, and summer weather patterns and conditions. Stratification is the result of a density differential between surface and bottom waters. This density difference in Long Island Sound is primarily a function of temperature differences between surface and bottom waters, with salinity differences contributing only slightly. The stratification of the water column sets up in the late spring or early summer and restricts the mixing of highly oxygenated surface waters with the oxygen depleted bottom waters. The larger the temperature and salinity differences between surface and bottom waters, the stronger the barrier to oxygen movement.

Weather conditions, patterns and events that are important to the development and characteristics of hypoxia include air temperatures, precipitation, and wind events. These weather patterns and events are responsible for water temperatures, salinity patterns, the timing and volume of runoff, including spring snowmelt, and the timing of water column mixing events. The variability in weather patterns contributes to the annual variability in hypoxia through its effects on nutrient delivery and water column mixing.

METHODS

Study Area

Long Island Sound is a semienclosed estuary located in the eastern United States with openings to the Atlantic Ocean at both its western and eastern ends (Figure 1). The western end connects to the Atlantic Ocean via a tidal strait, the East River, which connects to the lower Hudson River at New York Bay. The connection to the Atlantic Ocean at the eastern end of the Sound is larger and more direct, contributing most of the volume and tidal flow that control circulation and tidal patterns. The Sound is approximately 200-km long and 40 km at its widest point. It is bordered by the states of Connecticut (to the north) and New York (to the west and south) with 90% of its freshwater inputs coming from the Connecticut, Housatonic, and Thames Rivers (LISS 1994). With a surface area of approximately 3,366 square kilometers (including embayments) and a variety of habitat types, Long Island Sound has diverse marine faunal and floral assemblages including important recreational and commercial fisheries (LISS 1994). Its value to the region, which has more than five million people living within twenty-five kilometers of its coast, is both

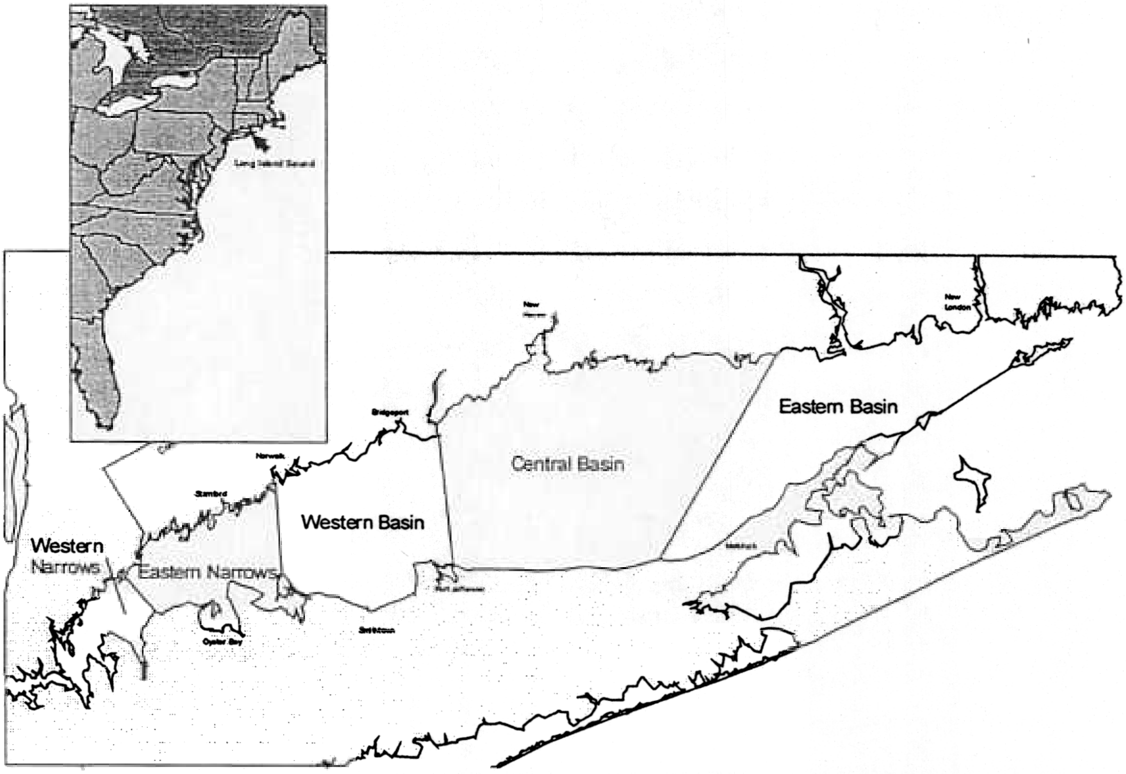


Figure 1. Long Island Sound study area showing basins. Inset shows location along the U.S. east coast.

economic and aesthetic. With so many people living in close proximity to its shores and with a drainage basin of 41,000 km^2, Long Island Sound has been the recipient of a wide range of anthropogenic pollutants. There are forty-four Publicly Owned Treatment Works (POTWs) discharging directly into the Sound and more than eighty throughout the Connecticut portion of the watershed alone. These POTWs, or sewage treatment plants, are significant sources of nutrients to LIS.

Area/Stations Sampled

1991-1993

CTDEP began intensive summer dissolved oxygen monitoring in June of 1991. During the summers of 1991-1993 most of the summer dissolved oxygen sampling was conducted as part of a cooperative intra-agency effort between the Bureau of Natural Resources and the Bureau of Water Management. This sampling was designed to evaluate the effects of dissolved oxygen concentrations on fish abundance as well as to determine the temporal and spatial extent of hypoxia. Sampling sites were randomly selected within defined areas that extended from the middle of the Western Narrows to the southwestern corner of the Eastern Basin, with a higher

Table 1. Summer dissolved oxygen monitoring 1991-1993.

Year	Cruise	Dates	# Stations Sampled
1991	WQJUL91	7/08-7/18	40
	WQAUG91	7/29-8/13	46
	HYAUG91	8/21-8/28	36
	WQSEP91	9/04-9/12	16
1992	HYJUN92	6/29-7/02	33
	WQJUL92	7/07-7/20	42
	HYJUL92	7/27-7/30	41
	WQAUG92	8/05-8/13	40
	HYAUG92	8/17-8/28	56
	WQSEP92	9/01-9/09	12
1993	HYJUN93	6/28-7/02	42
	WQJUL93	7/07-7/15	48
	HYJUL93	7/26-7/29	46
	WQAUG93	8/02-8/12	58
	HYAUG93	8/17-8/26	55
	WQSEP93	9/07-9/09	12

concentration of sampling sites per area in the west where hypoxia was generally more severe (Simpson et al. 1994). Sampling effort was also divided between two depth strata. Trawling was combined with water quality data collection for 226 samples and 294 additional samples for water quality alone were taken. A further discussion of this sampling design and the results of the living resource trawling component can be found in Simpson *et al.* (1994). The trawling surveys were supplemented by sampling conducted as part of the LIS Monthly Ambient Water Quality Monitoring Program at an additional seven stations each month (Figure 2). Some of these sampling events were combined into "cruises" for purposes of data analysis, in particular for calculating the area of hypoxia where coverage from two consecutive sampling events improved data interpretation and analysis. In total, combining both the trawl surveys and the water quality surveys, four to six sampling cruises were conducted each of these years, with from 12 to 58 stations being sampled each cruise (Table 1).

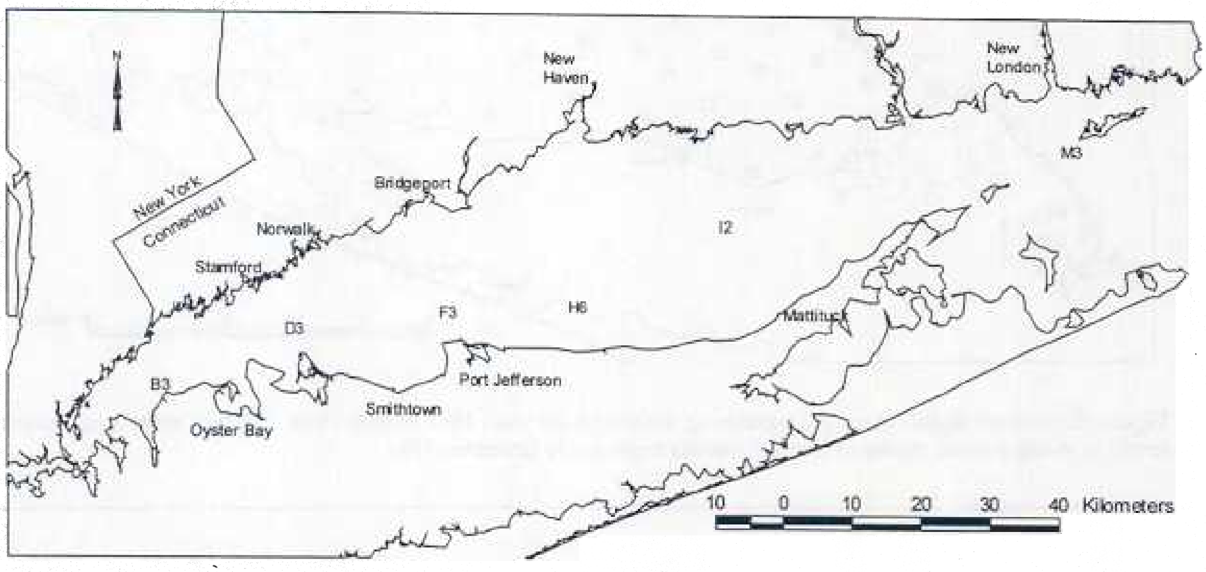


Figure 2. Connecticut DEP monthly water quality sampling stations in Long Island Sound for the years 1991 through 1994.

1994 – 1998

In 1994, 48 permanent sampling stations were established to monitor hypoxia. Eighteen of these permanent stations were also sampled as part of the monthly water quality monitoring program, which was expanded from seven to eighteen stations in December 1994. In 1998 one additional station was added in the Eastern Basin (Station J4). From 1994 through 1998 summer dissolved oxygen monitoring was conducted at these 48 (or 49) stations (Figure 3 and Table 2). These stations were concentrated in the western Sound, where low dissolved oxygen conditions have typically been most severe. Stations ranged in depth from 9 to more than 40 meters, and included a variety of physical characteristics. Six to seven cruises were conducted each summer, with from 6 to 48 stations being sampled each cruise for a total of 1,170 station profiles (Table 3). An effort was made to sample as many stations as possible given constraints of time and weather conditions. In some cases, when no hypoxia was observed in the western Sound or when the pattern of dissolved oxygen concentrations was evident from stations sampled (*e.g.*, a large area of western or central LIS with dissolved oxygen concentrations above 5.0 mg/L), stations in the far eastern part of the Sound, where dissolved oxygen concentrations generally do not fall below 5.0 mg/L, were not sampled.

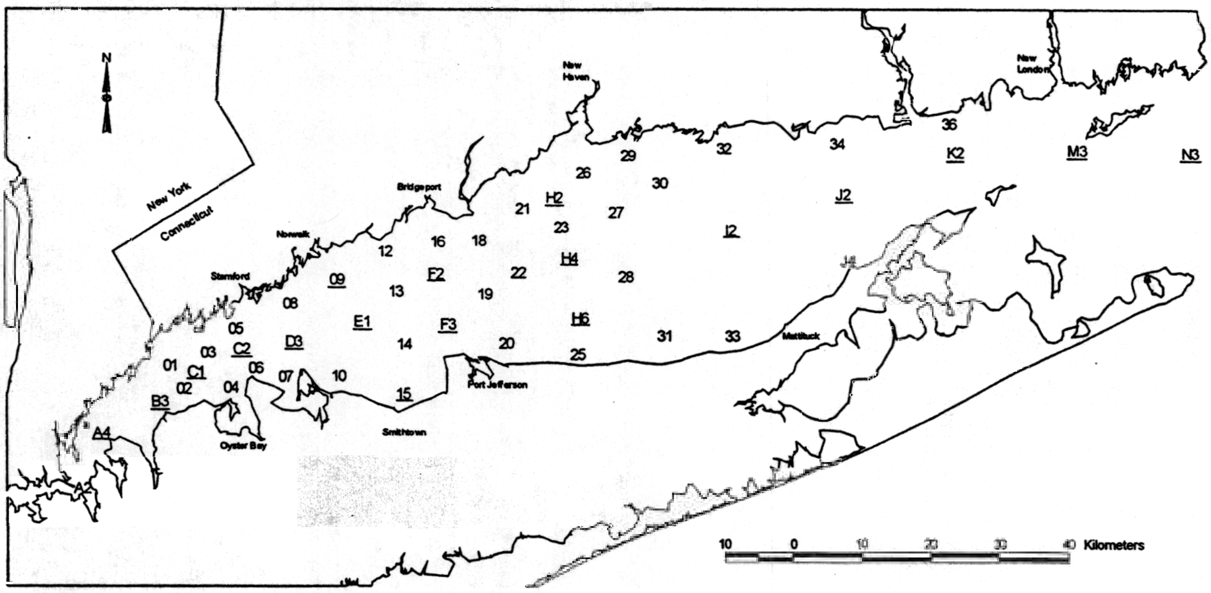


Figure 3. Summer dissolved oxygen monitoring stations for the years 1994 through 1998. Eighteen underlined stations also served as monthly water quality monitoring stations beginning in December 1994.

Table 2. Station information for all fixed stations sampled since June 1994 (see Figure 3).

Station	Station Depth (meters)	Latitude	Longitude	General Schedule	Sampling Dates	Notes
Narrows						
A2	29.2	40 48.05N	73 47.24W	Year round	4/91 - 11/94	sampled by NYCDEP
A4	32.6	40 52.35N	73 44.05W	Year round	8/94 - present	
B3	18.0	40 55.10N	73 38.57W	Year round	2/91 - present	
01	14.8	40 57.80N	73 37.42W	Summer	6/94 - present	
02	15.8	40 56.08N	73 36.04W	Summer	6/94 - present	
C1	19.8	40 57.35N	73 34.82W	Year round	12/94 - present	
03	24.1	40 58.76N	73 33.64W	Summer	6/94 - present	
04	12.3	40 56.27N	73 31.16W	Summer	6/94 - present	
C2	32.4	40 59.06N	73 30.13W	Year round	12/94 - present	
05	13.0	41 00.56N	73 30.82W	Summer	6/94 - present	
06	18.2	40 57.67N	73 28.60W	Summer	6/94 - present	
07	12.7	40 57.02N	73 25.52W	Summer	6/94 - present	
08	12.9	41 02.45N	73 25.08W	Summer	6/94 - present	
D3	40.9	40 59.63N	73 24.68W	Year round	2/91 - present	
Western Basin						
09	9.1	41 04.25N	73 20.17W	Year round	6/94 - present	
10	17.3	40 57.10N	73 19.95W	Summer	6/94 - present	
E1	38.1	41 01.16N	73 17.48W	Year round	12/94 - present	
12	10.5	41 06.52N	73 15.18W	Summer	6/94 - present	
13	22.3	41 03.50N	73 14.06W	Summer	6/94 - present	
14	25.4	40 59.49N	73 13.13W	Summer	6/94 - present	
15	15.3	40 55.88N	73 13.27W	Year round	6/94 - present	
16	8.9	41 07.22N	73 09.75W	Summer	6/94 - present	
F2	19.7	41 04.82N	73 09.92W	Year round	12/94 - present	
F3	40.9	41 01.07N	73 08.67W	Year round	1/91 - present	
Central Basin						
18	12.6	41 07.34N	73 05.40W	Summer	6/94 - present	
19	25.5	41 03.32N	73 04.85W	Summer	6/94 - present	
20	22.5	40 59.64N	73 02.54W	Summer	6/94 - present	
21	14.3	41 09.84N	73 00.89W	Summer	6/94 - present	
22	26.9	41 04.94N	73 01.37W	Summer	6/94 - present	
H2	13.9	41 10.68N	72 57.63W	Year round	6/94 - present	
23	19.0	41 08.41N	72 56.93W	Summer	6/94 - present	
H4	23.7	41 06.10N	72 56.04W	Year round	6/94 - present	
H6	41.4	41 01.56N	72 54.81W	Year round	1/91 - present	
25	10.7	40 58.86N	72 55.09W	Summer	6/94 - present	
26	11.2	41 12.55N	72 54.51W	Summer	6/94 - present	
27	20.2	41 09.52N	72 50.97W	Summer	6/94 - present	
28	30.1	41 04.69N	72 50.01W	Summer	6/94 - present	
29	9.4	41 13.89N	72 49.78W	Summer	6/94 - present	
30	15.3	41 11.78N	72 46.52W	Summer	6/94 - present	
31	25.8	41 00.25N	72 46.10W	Summer	6/94 - present	
32	10.7	41 14.49N	72 39.94W	Summer	7/94 - present	
I2	27.3	41 08.25N	72 39.30W	Year round	1/91 - present	
Eastern Basin						
33	20.2	41 00.23N	72 39.07W	Summer	6/94 - present	
34	16.7	41 14.76N	72 28.10W	Summer	6/94 - present	
J2	21.8	41 10.92N	72 27.46W	Year round	6/94 - present	
J4	18.5	41 05.85N	72 27.00W	Summer	6/98 - present	
36	6.6	41 16.23N	72 16.53W	Summer	7/94 - present	sampled infrequently
K2	37.7	41 14.06N	72 15.95W	Year round	7/94 - present	
M3	72.6	41 14.23N	72 03.20W	Year round	1/91 - present	
N3	52.9	41 14.00N	71 51.46W	Year round	1/95 - present	

Table 3. Summer dissolved oxygen monitoring 1994-1998.

Year	Cruise	Dates	# Stations Sampled
1994	HYJUN94	6/21-6/23	38
	WQJUL94	7/05-7/11	44
	HYJUL94	7/20-7/22	34
	WQAUG94	8/01-8/04	42
	HYAUG94	8/16-8/18	37
	WQSEP94	8/29-9/01	37
	HYSEP94	9/07-9/08	9
1995	HYJUN95	6/22-6/27	28
	WQJUL95	7/06-7/11	38
	HYJUL95	7/18-7/20	42
	WQAUG95	7/31-8/04	48
	HYAUG95	8/14-8/16	39
	WQSEP95	9/05-9/12	18
1996	HYJUN96	6/25-6/27	29
	WQJUL96	7/08-7/11	39
	HYJUL96	7/23-7/25	40
	WQAUG96	8/05-8/08	42
	HYAUG96	8/20-8/22	39
	WQSEP96	9/03-9/06	28
	HYSEP96	9/20	11
1997	HYJUN97	6/27-6/30	21
	WQJUL97	7/08-7/09	20
	HYJUL97	7/22-7/24	33
	WQAUG97	8/04-8/07	46
	HYAUG97	8/19-8/22	42
	WQSEP97	9/02-9/05	35
	HYSEP97	9/17	6
1998	HYJUN98	6/24-6/26	35
	WQJUL98	7/06-7/09	46
	HYJUL98	7/21-7/23	43
	WQAUG98	8/03-8/06	48
	HYAUG98	8/17-8/21	46
	WQSEP98	8/31-9/03	46
	HYSEP98	9/15-9/17	21

Equipment

Water sampling was conducted with the cooperation of CTDEP's Bureau of Natural Resources' Fisheries Division aboard the 50-ft R/V *John Dempsey*. Conductivity-temperature-depth (CTD) water column profiles were taken with a Sea-Bird model SBE-19 SeaCat Profiler, further equipped with dissolved oxygen (YSI model 5739) and photosynthetically-active radiation (PAR) (Licor spherical underwater model 193SA) sensors. The profiler unit had an internal memory to store temperature, conductivity, pressure, dissolved oxygen, and PAR data at a rate of twice per second as the unit was lowered through the water column. The instrument calculated secondary parameters of salinity, depth, and density and generated these data values as well. The data were generally reviewed in real-time (*i.e.*, as the profile was taking place) via the onboard computer and were uploaded to the computer during or after cast completion. Generally, the CTD unit was mounted on a rosette water sampling device (General Oceanics model 1015 Rosette Multi-Bottle Array) which could also hold up to nine, 5-liter Niskin water sampling bottles. These bottles were open as the rosette was deployed and were closed to collect a water sample when the real-time readout from the CTD indicated that the desired water sampling depth had been reached on the upcast. The rosette triggering device was powered through an electromechanical hydrocable attached to a deck command unit in the onboard laboratory, allowing remote actuation of the water sampling bottles.

A Turner Designs Model 10 Field Fluorometer was used to estimate chlorophyll *a* concentrations (an estimate of phytoplankton biomass) from whole water samples.

Measurements

The CTD unit described above provided measurements of salinity, temperature, dissolved oxygen, and light throughout the water column from the surface to the bottom at each station. These measurements were recorded twice per second by the instrument as it was lowered through the water column at a rate of approximately 0.2 meters/second. Water samples collected at selected depths via the Niskin bottles were analyzed for chlorophyll *a* and chemical dissolved oxygen concentration. These chemical and physical measurements are fundamental indicators of water quality, with specific relevance to hypoxia. These measurements provide:

- Evidence of changing conditions in the Sound
- Baseline information for the interpretation of related biological measurements from monitoring and research
- A Sound-wide baseline that localized monitoring and research programs can use for the purpose of comparing and corroborating their data

Chemical

Water samples were collected at a minimum of two depths. Surface water samples were collected approximately two meters below the surface; near-bottom water samples were generally collected between one and two meters off the bottom. Mid-water samples were regularly taken at one, two, or three additional depths, depending on the station depth.

Water samples were filtered in the onboard laboratory and filters were delivered to the analytical laboratory of the Environmental Research Institute (ERI) at the University of Connecticut for analyses of chlorophyll *a* using a standard fluorometric method, described in ERI□s Standard Operating Procedures for the Long Island Sound Study (ERI 1991). Whole (unfiltered) water samples were analyzed in the field using the field fluorometer for chlorophyll *a* estimations. These chlorophyll data will be reviewed in a future report. Winkler titration (azide modification) for determining the dissolved oxygen content of the water (AWWA 1992) were performed in the onboard laboratory as a quality assurance check of the CTD dissolved oxygen sensor performance. Dissolved oxygen sensor calibrations were performed at least monthly, usually prior to each cruise, using methods recommended by the manufacturer. All field procedures for sample collection and handling followed strict protocols detailed in the Program's Water Quality and Hydrographic Surveys Standard Operating Procedures (SOP) Manual (CTDEP 1991).

Physical

Physical parameter measurements (salinity, temperature, and density) were made with the use of the CTD water column profiling instrument, described above. The profiler was lowered through the water column at a rate of approximately 0.2 meters per second. Factory calibrations were conducted approximately annually on the conductivity and temperature sensors. Field procedures for instrument handling are detailed in the Program's SOP (CTDEP, 1991).

Cruise Identification

For purposes of hypoxic area calculations and trend analyses all samples were associated with a particular cruise. Each summer month (June through September) had two cruises: an early "water quality" cruise and a later "hypoxia" cruise (Tables 1 and 3). Cruise names include a 2-letter prefix, either "WQ" for "Water Quality" indicating sampling was conducted as part of, or, in the case of 1991-1993 sampling, close in time to the monthly water quality cruise. Monthly water quality cruises were generally conducted during the first week of each month. "HY" at the beginning of the cruise name is short for "Hypoxia", indicating the special summer cruises conducted approximately midway between monthly water quality cruises during the summer months. The "WQ" or "HY" prefix is followed by a 3-letter month identifier (JUN, JUL, AUG, or SEP) and then by a 2-digit year (91, 92, etc). Water Quality cruises included additional sampling for dissolved and particulate nutrient concentrations (data reported separately) at master stations (18 since December 1994) whereas Hypoxia cruises did not include such sampling. 1991-1993 cruise data was from two surveys (Water Quality and Fisheries Resource/Hypoxia Surveys) so that most of the cruise sampling periods were of longer duration than during 1994-1998 (Table 4).

Table 4. Range of dates during which sampling was conducted for each cruise ID.

Cruise ID	Range of Dates 1991-1998	Range of Dates 1994-1998
HYJUN	June 21 – July 2	June 21 – June 30
WQJUL	July 5 – July 20	July 5 – July 11
HYJUL	July 18 – July 30	July 18 – July 25
WQAUG	July 29 – August 13	July 31 – August 8
HYAUG	August 14 – August 28	August 14 – August 22
WQSEP	August 29 – September 12	August 29 – September 12
HYSEP	September 7 – September 20	September 7 – September 20

Data Presentation

Time series of bottom water dissolved oxygen concentrations are organized and presented by basin and station (Appendix A). Where available, data are included from the year-round monthly monitoring to give a complete record of the annual bottom water DO cycle. In addition, data from the Interstate Sanitation Commission (ISC) are included to supplement the data set. Appendix B, also organized by basin and station, provides a summary of data from all fixed sampling stations. Mean minimum DO for each summer cruise (HYJUN, WQJUL, HYJUL, etc.) is plotted showing the general seasonal trend at each station. Also plotted are the highest and lowest minima for each cruise ID (i.e. the range) and the standard deviation associated with the mean. Appendix C is a series of maps, organized by year and cruise, showing the stations sampled and the estimated area of Long Island Sound with a) minimum dissolved oxygen concentrations less than 3.0 mg/L (area of hypoxia, in black), b) minimum DO concentrations between 3.0 and 5.0 mg/L (areas in gray), and c) minimum DO concentrations of 5.0 mg/L or greater (white areas).

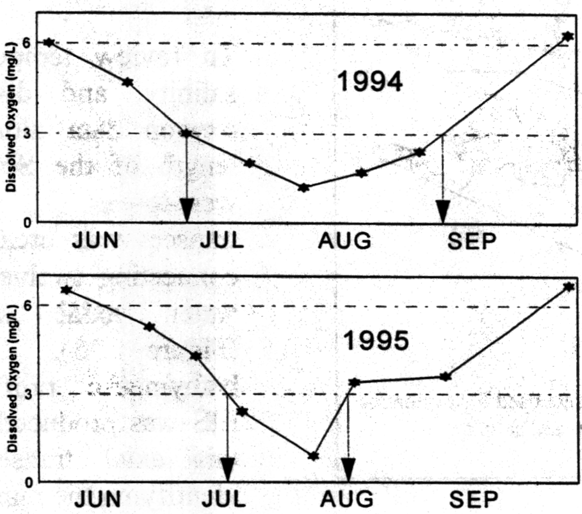


Figure 4. Bottom water dissolved oxygen observations at station B3, June through October 1994 (top) and 1995 (bottom). Arrows indicate approximate date (Julian date scale) of start and end of hypoxic event at this station.

Timing, Duration, and Area of Hypoxia

The beginning and end dates of each annual hypoxic event in Long Island Sound were estimated using time series of bottom water dissolved oxygen concentrations at each station (Appendix A and Figure 4). Figure 4 shows two time series examples for station B3 from the summers of 1994, when duration of hypoxia was relatively long at 68 days, and 1995, when duration was short, at 35 days. Start and end dates were approximated for each station by determining the intersection of the time series line (drawn with straight lines connecting sequential observations) with the 3.0-mg/L grid line (Figure 4). The earliest start date and the latest end date derived by this method, regardless of station, provided the preliminary start and end date estimates for the year. Data available from other programs and agencies, as well as daily wind and precipitation records were then considered. Such supplementary data improved the date estimates by filling in gaps between sampling events and accounting for substantial wind or storm events that would likely have provided the energy necessary to mix the water column when such events occurred between an actual sampling date and an estimated date. The duration of hypoxia was then estimated as the number of days from the earliest estimated start date to the latest estimated end date.

The minimum dissolved oxygen concentration and the location of each station sampled during each cruise was entered into a Geographic Information System (ArcView) database and plotted on a map of Long Island Sound. The Spatial Analyst extension in ArcView was used to interpolate DO values between stations using the inverse distance weighted (IDW) method. In this way a grid of minimum DO values for the entire sound was generated. The area within each dissolved oxygen interval (0.0-0.99 mg/L, 1.0-1.99 mg/L, 2.0-2.99 mg/L, etc) was estimated by counting the number of cells in the grid with values in each interval then multiplying the number of cells by the area of each cell (approximately 0.1 square km). The estimated total area included in this analysis was based on a line drawn at approximately the 4.0 meter depth contour, with the exception of the western and eastern boundaries of the Sound and where the line crossed the mouth of large bays, harbors and rivers into which our sampling did not extend. This area boundary line can be seen on all of the maps in Appendix C. The total calculated study area was 2723 square kilometers (km^2).

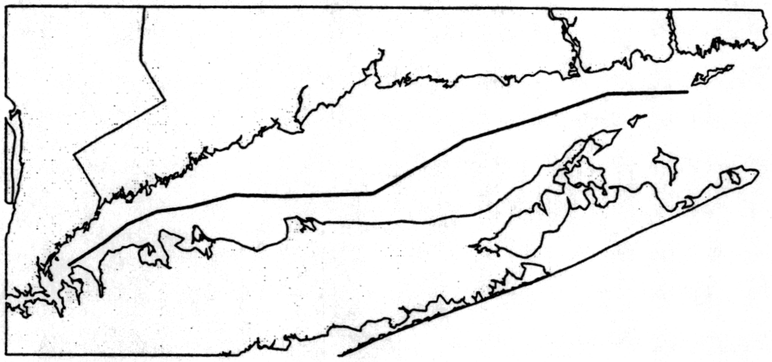


Figure 5. Map of Long Island Sound showing axial transect used for evaluating west to east distributions of dissolved oxygen, temperature, and salinity.

Axial Profiles

To review temperature, salinity, and dissolved oxygen data along the length of the Sound, a west-to-east axial transect was created by connecting twelve deep-water axial stations (Figure 5). A bathymetric profile of LIS was produced along this axial transect by identifying the maximum depth along each of a series of north-to-south transects drawn from points along the axial transect and separated by one nautical mile. The maximum depth at each of these points was determined from a 1983 NOAA 1:80,000 scale nautical chart using the mean low water depths. The resulting path of the west-to-east axial transect through Long Island Sound is shown in Figure 5 and approximates the thalweg of the Sound. This axial transect cross-section allows a graphical display of data to show surface-to-bottom and east-to-west differences in the water column throughout the length of Long Island Sound. By plotting temperature (isotherms), salinity, and dissolved oxygen data in this manner, differences in the pycnocline depth between stations and over time can be seen. Additionally, differences in the volume of water affected by hypoxia, between stations and over time, can be graphically represented. This report includes only a small number of these distribution plots by way of example (see *Vertical Dissolved Oxygen Distribution* and *Axial Profiles* sections of Results and Discussion).

Trend Analyses

Data from 1994 through 1998 were analyzed for significant trends in summer dissolved oxygen concentrations. Summer DO data from earlier years (pre-1994) were not included in this trend analysis because of the difference in sample design, in particular the use of random versus fixed station locations. The minimum dissolved oxygen concentrations observed for each station during each sampling event were first deseasonalized to remove the effects of serial correlation in the data (Bauer et al. 1984). A cruise mean and associated sample standard deviation were calculated for each station. To deseasonalize the data, the cruise mean was subtracted from each of the individual observations (measurements) to obtain the "deseasonalized" data. It was these data that were used for statistical trend analysis.

The deseasonalized data for dissolved oxygen concentrations from each station were put into a frequency distribution and were evaluated using a Chi-square test to determine whether they fit the normal distribution model. If the data set fit the normal distribution model, a seasonal linear regression (parametric method) was plotted, and a Student's t-distribution used to determine the significance of the slope (and thus whether a statistically significant trend existed). If the deseasonalized data set did not fit the normal distribution model a seasonal Kendall's test (nonparametric method) was used to determine whether a statistically significant trend existed. In such cases the Kendall slope estimator was used to estimate the rate of change. Trends were considered significant if the p-value was less than 0.05 (significance level of 95%).

The above-described analyses were applied to the 1994-1998 summer DO data from fixed stations sampled where sufficient data was available. In addition, data collected by the Interstate Sanitation Commission (ISC) (Interstate Sanitation Commission 1991 – 1998) were used to supplement CTDEP dissolved oxygen data in the western portions of Long Island Sound. An explanation of the stations sampled and the methods used in the ISC special survey, Ambient Water Quality Monitoring in Long Island Sound to Document Dissolved Oxygen Conditions, is available in ISC Annual Reports (ISC 1992 – 1999).

RESULTS/DISCUSSION

Schedule

Over the eight-year period from 1991 through 1998, and during the three-month period from mid-late June through mid-late September (*i.e.*, summer months), a total of 50 sampling cruises were conducted by the CTDEP (Tables 1 and 3). From 1991 through 1993, cruises conducted as a cooperative intra-agency effort to evaluate both the temporal and areal extent of hypoxia as well as the effect of dissolved oxygen concentrations on living resource abundance as estimated from trawl catches were included (Simpson et al. 1994). Beginning in 1994, the intensive summertime dissolved oxygen monitoring no longer included a living resource trawling component. The Department's Bureau of Water Management focused the intensive effort on observing dissolved oxygen concentrations throughout the Sound, with coincident measurements of additional chemical and physical water quality parameters.

CTD Profiles

Over all eight years a total of 1752 station profiles were taken. Figure 6 provides examples of the water column profile data obtained with the CTD, showing results from nine consecutive surveys from May through October 1996 at station D3. These profile data, in their entirety, are available for those wishing to pursue additional analyses.

General Dissolved Oxygen Observations

Generally, the patterns observed concerning dissolved oxygen concentrations in LIS were consistent from year to year and included:

- Stations exhibited a distinct seasonal pattern with respect to DO concentrations